THINNING FOR INCREASED WATER YIELD IN THE SIERRA NEVADA MOUNTAINS: FREE LUNCH OR PIE IN THE SKY?

Michael D. Purser, Consulting Hydrologist, Bellevue, WA
Jonathan J. Rhodes, Hydrologist, Planeto Humado y Azul Hydrology, Portland, OR

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About the Authors

Jonathan J. Rhodes is a professional hydrologist with an MS in hydrology and hydrogeology and 17 years of professional experience. His current work focuses on the protection of anadromous fish habitats from non-point source pollution. His MS thesis was on nitrate transport in snow and snowmelt in the high Sierra near Lake Tahoe. He served as consulting hydrologist for the Tahoe Regional Planning Agency in '87 and '88 and has published several peer-reviewed papers on snowmelt and water quality in the Sierra Nevada.

Michael D. Purser, a professional hydrologist and soil scientist with 16 years professional experience, has focused on the impacts of dispersed land management to water quality and fish habitat. Born and raised in California, he has worked for the USDA-Forest Service in the Sierra Nevada and elsewhere, in academia, with Indian tribes, and as a consultant.

THE PACIFIC RIVERS COUNCIL

Main Office
PO Box 10798
Eugene, OR 97440
ph: 541-345-0119
fax: 541-345-0710

California Office
PO Box 6185
Albany, CA 94706
ph: 510-548-3887
fax: 510-548-3776

Offices Also In:

Portland
921 SW Morrison, Suite 531
Portland, OR 97205
ph: 503-294-0786
fax: 503-294-1066

Seattle
PO Box 4735
Seattle, WA 98104
ph: 206-447-4186
fax: 206-343-1526

Washington, D.C.
605 Prince
Alexandria, VA 22314
ph: 703-836-3420
fax: 703-836-4055

Tennessee
7131 Candies Creek Ridge Rd.
Charleson, TN 37310
ph: 423-336-2605
fax: 423-336-2706

Mission of the Pacific Rivers Council

To develop scientific tools, legislative policies and community enhancement strategies to restore the ecological integrity and sustainable human use of America's river systems.

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I. Introduction

It has been posited that forest/ecosystem health-related thinnings[1] in the National Forests of the Sierra Nevada would produce the "benefit" of increasing annual water yield[2] and/or baseflow[3] for use by downstream users. This would theoretically occur as a result of decreasing evapo-transpiration and canopy interception and increasing snow accumulation. The precipitation then not transpired or intercepted by the trees would runoff, entering streams, or infiltrate and enter the groundwater to become baseflow.

However, this simple model is fraught with several problems. Evidence of a clear relationship between thinning and increased baseflow does not exist. Even when an area has been clearcut logged, an increase in annual water yield does not always result. The reasons for this are many and include increased runoff during the wet season (yielding higher peakflow[4]), snowpack loss due to increased sublimation and other effects, and soil compaction and surface soil loss resultant from ground-based forest management operations (reducing infiltration, soil moisture storage, and permeability).

The ecological costs of increasing annual water yield may be steep. Logging at an intensity (percent area devegetated) that is likely to result in increased annual water yield would also result in increased peakflow. That is, flood peaks would be higher, exacerbating downstream flooding. The downstream flooding would be likely to increase channel erosion and damage downstream property. The effects of increased peakflow could be long-lived while increased baseflows may be transient or even reduced in the long term. It appears that a significant portion of a watershed must be kept in a clearcut or otherwise devegetated state to increase annual yield. Such deforestation would also shift the timing of peak flows earlier in the season (McIntosh, 1992), adding to already high flows and providing little useful benefits to downstream beneficiaries.

Logging and logging-related activities such as roads would dramatically increase erosion and sedimentation, degrading water quality and fish habitat, reducing reservoir capacity, and possibly incurring greater water treatment costs. In fact, a logging program intensive enough to be associated with increased annual water yield and peakflow would be accompanied by levels of erosion and sedimentation which may violate the National Forest Management Act, the Clean Water Act, the Endangered Species Act, the various Forest Plans, state law, and county comprehensive plans and regulations.

Notably, the combination of increased peak flows and increased erosion would sharply decrease aquatic habitat quality with a resulting increase in local extinction of sensitive aquatic species,

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[1] Thinning, as referred to in this paper, is a silvicultural activity which is designed to increase the growth of remaining trees through the theoretical provision of a greater share of the water and nutrients available at a site.
[2] Annual water yield is the total surface runoff from a watershed over the calendar or water year (October 1 through September 30).
[3] Baseflow is that component of the surface water hydrograph which is not derived from direct precipitation, overland flow, or return flow resulting from storm events.
[4] Peakflow is the annual high stream discharge (volumetric flow rate). Statistically, in 9 years out of 10 in the mountainous west, this is the discharge resulting from the annual snowmelt event, usually taking place in the period April to June.

including salmonids. West-wide, salmonids and other species dependent on cold, clean water are facing extirpation from causes at least partly related to logging and logging-related activities.

This paper examines these problems including:
1) the likely effectiveness of thinning for the purpose of increasing water yield (e.g., direct effects on streamflow, evapo-transpiration, snow accumulation);
2) the resulting impacts to peakflow, baseflow, and downstream users;
3) the impacts of thinning operations on infiltration, soil erosion, water quality, soil moisture storage, and percolation (transmission to groundwater);
4) the impacts of increased soil erosion and downstream sedimentation on forest/soil productivity and reservoir capacity; and
5) the cumulative impacts to fish habitat and survival.

Finally, we offer some low-risk, well-understood alternatives which will improve baseflow conditions and decrease peakflow through increased infiltration and groundwater storage (Harrison, 1991). These actions would have the added benefits of improving water quality and contributing to reduction in flooding. These alternative actions include road obliteration, prevention of soil compaction, restoration of beaver populations, and greatly reducing or suspending livestock grazing.

II. Thinning For Increased Water Yield

There appears to be no direct evidence that thinning would increase baseflow. Theoretically, devegetation serves to increase all flows (peak, annual, base) by reducing evapo-transpiration and canopy interception and by increasing snow accumulation. However, thinning operations such as might occur in the Sierra Nevada would not likely remove sufficient vegetation to override mechanisms which would make use of additional water (e.g., revegetation). In fact, the literature clearly indicates that extensive and permanent deforestation is required for significant annual yield increases. There is no long-term or experimental study showing that "thinning" can increase streamflow. In fact, studies of the impact of clearcut logging on water yields have shown mixed results. For instance, roads and logging increased peakflows in some watersheds dominated by rainfall (Jones and Grant, 1996) but not in others (Ziemer, 1981).

Studies of changes in streamflow caused by the removal of vegetation have generally found that annual yields are increased when large areas of coniferous forests are clearcut and/or roaded (Bosch and Hewlett, 1982; Cheng, 1989; MacDonald and Ritland, 1989; Hicks et al., 1991a; King, 1989). The studies of these changes generally indicate that increases in flows are greatest during the wet periods, such as the annual peakflow, and/or snowmelt period/event (Bosch and Hewlett, 1982; King and Tennyson, 1984; King, 1989; Berris and Harr, 1987; Cheng, 1989; MacDonald and Ritland; 1989; Hicks et al., 1991a; Swanson et al., in process), while changes in baseflow were mixed (Hicks et al., 1991a). Bosch and Hewlett (1982) reviewed data from 94 catchment experiments. They noted that while few researchers measured the effects of forest cover reductions of less than 20%, those experiments which did concluded that effects on annual water yield were not detectable.

Marvin (1996) reviewed the results of more than 30 studies of changes in annual yield with reductions in forest cover. All of the studies involved logging, fairly complete vegetation removal, or mortality over at least 25% of relatively small watersheds. Notably, in four of the five studies where 25-28% of the watershed was devegetated, there were no increases in annual water yield (Marvin, 1996). Further, all but one of the studies reviewed involved significant amounts of clearcut or burning; in the only study reviewed that involved only selection logging, there was no increase in annual water yield—a Colorado study where 40% of the watershed was logged in an area where snow is the dominant form of precipitation and snowmelt dominates the annual hydrograph (Marvin, 1996).

King and Tennyson (1984) and King (1989) were not reviewed by Marvin (1996) although the study setting in the snowmelt-dominated pine forests of Idaho with granitic soils renders the results somewhat applicable to the Sierra. King and Tennyson (1984) found that there was no statistically significant increase in annual water yield or baseflow when less than 5% of the watersheds were disturbed by roads. In contrast, the increases in the 25% exceedence flows were significant (King and Tennyson, 1984). After 25% to 36% of these same watersheds had been logged and roaded, the increase in annual water yield was significant; however, these changes were accompanied by statistically significant increases in peakflow[5] in all of the treated watersheds (King, 1989). These measures of peakflow were increased by 15% to 87% (the latter the maximum daily flow), indicating the changes in peakflow accounted for most of the statistically significant change in annual water yield.

Troendle (1985) documented the transient nature and dependence on annual precipitation of increases in annual yield and peakflow. Analysis of clearcut, partial cut (30-40%) and shelterwood cut watersheds in the Rocky Mountains showed that though initial, statistically significant increases in annual yield occurred, he attributed the increase to the greater-than-average precipitation for the years in which the increase was found and the large volume of timber removed. Further, Troendle noted that after the first three years, the increase from one of the clearcut areas (North Fork Deadwood Creek) could not be detected and four years after treatment the increase from the whole watershed (Deadwood Creek, 26 units, three different treatments each at 30-40% basal area removal) was not statistically significant. Regression analysis showed that the highest correlation with change in flow was with seasonal precipitation.

Fowler et al. (1987) found no significant increases in annual water yield of three small watersheds in northeastern Oregon after small clearcut (22% stand removed), larger clearcut (43% stand removed), and shelterwood (50% stand removed) treatments, compared to a control watershed (no cutting). They did find, however, that maximum air temperatures increased in the treated watersheds relative to the control, while wind passage and velocities increased dramatically compared to the control watershed. Harr (1976) found no statistically significant change in water yield for four watersheds in the Oregon Coast Range and Cascade Mountains which were cut by shelterwood prescription (30%) and patches (25%). Hetherington (1982) found no clear evidence of change in storm runoff from a clearcut covering 40% of the Carnation Creek watershed, but annual yield and baseflow decreased in some years.

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[5] Peakflow indices used in the study were the maximum monthly streamflow, the 5% exceedence flow, the maximum daily flow, and maximum instantaneous flow.

There are several reasons why significant amounts of clearcutting or nearly complete removal of vegetation may be necessary to increase annual water yields. Many of the subsidiary effects of logging actually decrease flow over time, and only massive deforestation overcomes these other factors. For instance, logging or thinning will release the remaining trees and other vegetation which will then use more water to support their accelerated growth rate. Opening canopies also increases evaporation and sublimation of snow. Golding and Swanson 's (1978) results indicate that the windward width of logged openings must be at least one tree height to significantly increase snow accumulation. Marvin (1996) also concluded that back-calculating evapotranspiration (= precipitation minus runoff) frequently results in overestimating water yield change from vegetation removal.

The literature reveals that while logging and logging-related activities can increase annual yield, however, a significant portion of the watershed (e.g., >25-30%) must be permanently deforested to produce sustained, useful, and predictable increases in water yield. This will not only result in increased annual yield and baseflows, but will result in increases and shifts in the timing of peakflow as well. Unless proposals for thinning propose to repeatedly log a significant part of the watersheds, increases in annual yields or baseflows are unlikely.

III. Understory Thinning Is Unlikely To Increase Stream Volume

There is good reason to doubt that understory thinning to release future crop trees would increase annual yield at all, particularly in the Sierra. Kattelmann (1987) found that much of the subalpine zone in California is at or near maximum water yield. Virtually the entire Sierra Nevada is moisture-limited during the low flow period. Simulation of net photosynthesis in the central western Cascades of Oregon shows greatly increased photosynthesis during the period from the end of June to early September when the effects of moisture stress are removed (Franklin, 1981). The vegetative cover absorbs any available soil moisture early in the season. If thinning were to remove the small-diameter understory trees, the remaining moisture-limited overstory and shrub layer would absorb any released moisture. The vegetative communities of the Sierra Nevada are superbly adapted to utilize available soil moisture. Thinning will not overcome that adaptation, and the average Sierra watershed will not likely yield an extra drop unless a fairly large portion of all the vegetation is removed. If thinning releases some soil moisture the effect would probably be to reduce the drought stress on the remaining large trees.

Additionally, runoff from upslope areas is likely to be captured by riparian vegetation, particularly as protection and restoration of riparian vegetation is more fully realized in support of meeting Forest Plan and Clean Water Act goals. In other words, any soil moisture made available by thinning most likely will never enter into the stream system. Hicks et al. (1991a) suggested that re-vegetation and changes in vegetation communities and compensatory vegetative response in riparian zones may have been the primary mechanism that reduced baseflows in their study in western Oregon.

IV. Thinning Can Contribute To Snowpack Loss

In snow dominated systems, removal or diminishment of the forest canopy can allow substantial increases in sublimation, the process by which snow evaporates back into the atmosphere. Logging activities that leave openings in the forest cover can increase this form of evaporation and thereby cancel out any positive runoff benefits that might have been created. Thinning in particular would be expected to increase sublimation by opening up the snowpack to wind, which is the major driver of sublimation.

One of the major mechanisms proffered for increased yield is increased accumulation of snow and reductions in canopy interception and subsequent evaporation/sublimation in openings. Golding and Swanson's (1978) results indicate that the windward width of logged openings must be at least one tree height to significantly increase snow accumulation; increased accumulation in these clearcuts is maximized when openings are about 2.2 tree heights in diameter, decreasing thereafter due to increased wind scour and sublimation (Swanson et al., in process). Openings increase windspeed over the snowpack (Berris and Harr, 1987; Fowler, et al., 1987); thinning probably increases windspeed incrementally. Windspeed is one of the dominant drivers of sublimation (Male and Gray, 1981). Small openings may have a nominal effect on increasing snow accumulation and reducing canopy interception while increasing sublimation to a nominal degree, canceling out potential increases in streamflow.

Sublimation in the Sierra can be significant. Szecody (1983) estimated that midwinter evaporation losses from the snowpack were in the range of 13-23% of the snowpack under undisturbed conditions in the eastern Sierra Nevada at an elevation range of about 6000 to 9000 ft. However, Szecody's (1983) research area was on the lee side of the Sierra in a moderately incised valley. Sublimation may be considerably higher on windward locations in more wind-exposed sites. Under optimal conditions for sublimation, up to 52% of the water equivalent of the snowpack can be lost to sublimation (Male and Gray, 1981).

While sublimation can be major in clearcuts because of increased wind and air temperature, it is unlikely to totally offset the effects of increased accumulation and reduced interception. Thinning may provide only nominal reductions in interception and evapotranspiration and nominal increases in accumulation while decreasing relative humidity and wind and increasing air temperature (Fowler, et al., 1987) thus leading to increased sublimation. The overall effect of thinning on snowpack is nominal at best and depends on the size of openings and percentage of precipitation as snow/elevation.

V. Resulting Impacts to Baseflows and Peakflows

A. Baseflow

As noted above, increases in baseflow from thinning operations are speculative. They appear to be possible based on theory, however, as Marvin (1996) and others have noted, the actual calculations based on theory are dependent on assumptions that may not be true. The calculations which show an increase in annual yield (i.e., surface runoff) assume that there is no drainage to groundwater (i.e., precipitation = runoff + evapotranspiration). The calculations also ignore the potential for the increased soil moisture to be utilized by the remnant or new vegetation. Surface runoff may be captured by downslope soil and/or vegetation before entering the channel (Heede, 1984; Purser and Cundy, 1992). Forest managers often count on this since an increase in surface runoff would necessarily lead to an increase in surface erosion (sheet and/or rill erosion), an undesirable byproduct of forest cutting.

Increases in summer baseflow in response to clearcut logging and roading have been found to be insignificant (King and Tennyson, 1984; King, 1989; Hicks et al., 1991a), or nominal in comparison to increases in peak streamflow (Cheng, 1989; Hicks et al., 1991a; Swanson et al., in process). It also appears that nominal increases in baseflow are transient while increases in annual yield and flow during wet periods in response to logging are more long-lasting (Hicks et al., 1991a; Troendle, 1985). Everest and Harr (1982) note that though clearcutting can increase baseflow, such increases are temporary and may disappear in less than 5 years.

Indeed, in at least one case, it appears that logging may have contributed to a decrease in baseflow. Hicks et al. (1991a) found that although clearcut logging appeared to result in a statistically significant increase in baseflow, this effect was highly transient. In one watershed the nominal increase in baseflow lasted only about 8 years, thereafter, baseflow appeared to be reduced relative to the pre-logging condition for 16 years (the watershed had been completely clearcut and burned). Another watershed exhibited increased baseflows for only about 16 years, after 25% of the watershed had been clearcut in patches.

Hicks et al. (1991a) found indications that frequent re-entry with clearcutting of 25% or more of the watershed would be required to maintain elevated baseflow. At the above rates, the entire watershed would need to be clearcut every 30-60 years to maintain increased baseflows. This of course is but a theoretical calculation. It would result in negative feedback which would likely end up reducing baseflow anyway (see below), and depends on clearcut logging, not thinning. Apparently, even complete clearcutting only provides transient increases in baseflows that can be followed by significant reductions in baseflow.

Areally extensive forest management operations such as thinning typically require the use of existing roads, landings, skid trails, etc., or create the need for additional roads, landings, trails, etc. The forest transportation system has long been recognized as the major detrimental effect on the forest, its productivity and the quality of the water it produces (e.g., Packer, 1965). Soil compaction (discussed in detail in the next section) resulting from road, landing, and trail construction and use, has direct and cumulative effects on watershed hydrology. The compaction reduces infiltration, percolation to groundwater, and soil moisture storage through reduction in overall pore space and the size of pores (Purser and Cundy, 1992).

Thus the additional water from snowmelt caused by the removal of canopy cannot be assumed to enter the groundwater system from which baseflow is derived. The likelihood is that the water will either runoff, where infiltration is reduced to below-snowmelt intensity, or will fill up the soil moisture capacity sooner and more often throughout the rain/snowmelt season yielding surface runoff in excess of that experienced by the pre-compaction watershed (Purser and Cundy, 1992).

Thus, compaction and soil loss from forest management operations can cause long term reductions in baseflow and increases in surface runoff, including peakflow.

B. Peakflow

Increases in peakflow can be expected from logging and logging-related activities. Studies in areas where streamflow is dominated by snowmelt consistently indicate that peakflow is increased by roads and logging (King and Tennyson, 1984; King, 1989; Berris and Harr, 1987; Cheng, 1989; MacDonald and Ritland; 1989;a et al., 1991a; Marvin, 1996; Swanson et al., in process). Changes in peakflow caused by logging and roads are more variable in areas where streamflow is primarily derived from rainfall than in areas where streamflow is primarily derived from snowmelt (MacDonald and Ritland, 1989). For instance, many studies in rain-dominated areas have shown no increase in water yield while others have shown increases. In rain-dominated areas, logging has been documented to increase runoff during the wet season to a greater degree than during dry summers (Hicks et al., 1991a).

In contrast, results of studies in snowmelt-dominated areas consistently indicate that when logging is extensive enough to increase annual water yields, the greatest increase occurs during peak snowmelt (Berris and Harr, 1987; King, 1989; Cheng, 1989; MacDonald and Ritland, 1989; Swanson et al., in process), including during rain-on-snow events (Berris and Harr, 1987: Harr and Coffin, 1992). Peak surface runoff is likely to be available at a time, in the Sierra (April through June), when peak snowmelt is occurring. The higher flood peaks would exacerbate downstream flooding. The effects on flooding could be long-lived while increased baseflows may be transient or even reduced in the long term.

There are several reasons why logging in snow-dominated areas consistently increases peakflow. Openings that are large enough to increase snow accumulation and decrease forest interception (> about 1 tree height according to Golding and Swanson [1978]) are large enough to increase snowmelt via increased solar radiation (King, 1989) and increase melt by sensible and latent heat transfer during rain-on-snow events (Berris and Harr, 1987). Solar radiation is the dominant aspect of the heat budget for snowpacks in the Sierra (Aguado, 1985).

However, rain-on-snow can be an important contributor to mid-winter flooding, especially in the transient snow zone. Berris and Harr (1987) found that measured outflow from logged plots in clearcuts during the largest rain-on-snow event during the study were about 21% greater than adjacent forested plots; intensive meteorological data on both plots confirmed that sensible and latent heat transfers dominated the heat budget during the event and were far greater in the clearcut plot. Harr and Coffin (1992) found that increased outflow from snowpacks in areas that had reforested after logging remained significantly higher than from old growth stands, even after several decades of regrowth.

Roads also increase peakflow by intercepting shallow subsurface flows at roadcuts. Interception of subsurface water by roadcuts has been consistently documented in a variety of settings (Megahan, 1972; King, 1989; Wemple et al., 1996). Atkinson (1978) noted that vertical cuts in hillslopes inexorably disrupt shallow subsurface flow paths by draining them during periods of high moisture content when saturated zones can develop behind the cut and effectively damming or re-routing them during periods of low moisture content. King (1989) and Wemple et al. (1996) noted that the conversion of relatively slow subsurface flows to relatively rapid surface flow observed in their research is likely mechanism for the increases in peakflow in logged and roaded environments.

The levels of deforestation required to increase water yield would also shift the timing of peakflow earlier in the season, the exact opposite of what might be useful to potential downstream beneficiaries (King, 1989; Cheng, 1989; McIntosh, 1992). Timing shift applies mainly to snow zones (McIntosh, 1992). Notably, the advancing of the snowmelt hydrograph occurred even in fairly large watersheds (Cheng, 1989; McIntosh, 1992). In small watersheds with low levels of disturbance, King (1989) did not find that the snowmelt hydrograph was significantly advanced in all cases. Advancement of the snowmelt hydrograph can exacerbate flooding in downstream areas.

With early snowmelt there is the very real potential for cumulative flood effects due to: a) greater synchronization with downstream runoff from rains; b) more runoff from higher elevation during periods of greater low elevation runoff and much greater degrees of saturation in lowlands, e.g. much less available soil moisture storage downstream (Fowler, et al., 1987). Recent flooding has caused significant and costly damage of public and private property. Additional logging is likely to exacerbate downstream flooding and attendant damage and costs.

VI. Increased Erosion And Soil Compaction from Thinning

Logging has several other effects, largely unavoidable, that cumulatively contribute to reductions in baseflow. These are largely the same effects that increase peakflow: soil compaction, soil loss, and the interception of subsurface flow by roads. Disruption of subsurface flow during low moisture content periods may be significant. Logging at a sufficient intensity to effect increases in streamflow/baseflow would result in dramatically increased erosion and sedimentation, many times higher than natural rates.

A. Surface Erosion, Soil Compaction and Soil Moisture Capacity

All forms of logging are directly associated with soil loss, related to trenching[6], scarification, road and landing construction and maintenance, compaction, and other processes. Soil loss is permanent and irreplaceable at human time scales (Curry, 1971; Brady, 1974) and is, therefore, cumulative in time and space. Harrison (1991) reported that land uses contributing to accelerated erosion in the East Branch of the North Fork Feather River include livestock grazing, timber harvesting, roads, and channelization of streams for flood control. Soil compaction-related increases in bulk density caused by logging and related activities have been found to be 10-50%, and, with concomitant reduction in infiltration rates and soil moisture storage, have been found to be persistent, especially in subsoil horizons, lasting 40 to 70 or more years (Froelich, et al., 1983).

[6] Extensive areas of the Sierra Nevada Range have been trenched from "donkey" (railroad) logging in the 1800's. This detaches and displaces topsoil leading to soil moisture storage and fertility problems.

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This in turn leads to the direct loss of water storage in soils at the watershed scale. Soil is the sponge of the watershed, and the loss of just one inch of soil (from logging or any other cause) results in a loss of nearly 1500 cubic feet of potential water storage capacity per acre, at soil porosity levels commonly encountered in the Sierra (40% porosity assumed). Even in a very small watershed of one thousand acres, the decreased watershed storage capacity associated with one inch of lost soil amounts to a staggering 1.5 million cubic feet or about 35 acre-feet per thousand acres.

Soil compaction reduces the infiltration of water into the soil, percolation to groundwater, and, through reduction in pore space and size, reduces the soil's moisture storage capacity. In the Sierra Nevada, much of the overland flow is generated from flow over saturated soil rather than due to exceedence of infiltration rates (e.g., Rhodes, 1985), so reductions in soil moisture storage capacity are likely to increase the frequency, magnitude and extent of overland flow, increasing peakflow. Partial cut logging with ground based equipment is known to disturb greater than 20% of an area in California (Froelich, 1988). Use of a feller-buncher caused up to 40% disturbance within the cut unit (Froelich, 1988). Soil erosion and compaction from roads, landings and skid trails will serve to exacerbate seasonal flow extremes (e.g., flooding), especially as watersheds are cumulatively roaded and impacted by logging and associated activities. So while the benefits from thinning are highly speculative, the watershed damage is certain.

Thinning with conventional ground-based equipment could cause unusually large amounts of soil compaction because of the very large areas to be treated. Removing a million board feet of timber through thinning could have more negative watershed effects than clearcutting a million board feet, because thinning would be conducted over many more acres to achieve the same volume. Thinning, in other words, may maximize certain kinds of watershed damage.

To minimize the watershed damage caused by logging, the area to be logged should be small, low in the watershed, use as few roads as possible, and be done infrequently. Thinning operations are typically just the opposite. They are intentionally conducted over very large areas using more road miles, are frequently conducted high up in the watershed, and require more frequent reentry than other forms of logging to achieve similar volume.

B. Logging Roads Contribute To Harmful Watershed Effects

The roads associated with thinning also would have very large negative watershed effects. There is a large and growing body of evidence that the road network increases flooding and erosion more than any other single factor in the forested landscape—the repercussions of which are felt throughout the Sierra and beyond, as recent landslides and floods demonstrate. Roads also contribute to loss in water storage capacity within the watershed due to removal of topsoil, soil erosion from flow concentrated by forest roads, and compaction of road and near road surfaces.

Roads significantly increase overland flow via compaction. Further, roads act as extensions of stream systems by routing overland flow to streams. This can increase peak flows by increasing the efficiency of overland flow delivery during rain and snowmelt events (Wemple et al., 1996). Extension of the stream network by roads has been documented to be extremely significant.

Wemple et al. (1996) found that the road network in two basins in the Oregon Cascades effectively increased the drainage density by 21 to 50%; about 57% of the surveyed road segments were hydrologically connected to streams by surface flowpaths.

Roads and logging also cause soil loss which can contribute to increased peakflow. Based on erosion rates used by the USFS to estimate erosion from roads in granitic terrain (Potyondy et al., 1991), it is estimated that a newly constructed road 20 feet wide would result in 425 tons of accelerated erosion over a decade. Assuming that 25% is completely exported out of the watershed via streamflow, this results in a loss of about 119 tons of soil/mile of road/decade, or about 2468 ft^3/mi./decade. Assuming a porosity of 0.4, this results in an accumulating loss of about 987 ft^3 of water storage/mile/decade. Although the magnitude of this effect is nominal over small timeframes and small unit areas, soil loss is completely cumulative spatially and temporally, with no recovery possible. Thus, over longer time periods with extensive disturbance, soil loss at the watershed scale can have an extremely significant effect on peakflow that is essentially permanent in human terms.

Although the design, location, and implementation of logging and road construction can provide some reduction in soil loss, hydrologic disruption, compaction, and sedimentation caused by the activities, there appears to be no good field evidence that it can reduce these effects to biologically and environmentally insignificant levels (ISG, 1996; Espinosa et al., 1997). Megahan et al. (1992) noted that in erosive granitic soils sedimentation from logging and road construction was inevitable regardless of how carefully it was implemented. USFS (1997) also stated that some sedimentation of streams from logging and roading was inevitable regardless of management practices.

Logging and logging roads typically accelerate sediment delivery to streams on the order of two to ten times natural rates (Geppert et al., 1984; MacDonald and Ritland, 1989). Logged areas contribute significant quantities of sediment to streams, especially in steep and/or erosive terrain or where proximate to streams (Everest et al., 1987; Hicks et al., 1991b). In Idaho, ground-cable logged areas erode at about 1.6 times natural rates per unit area, on average, over a six year period following logging (King, 1993). It appears that logging always causes some increase in sediment delivery to streams even when low impact logging systems are used in conjunction with vegetative buffers (Megahan, 1987; Heede, 1991) or existing Best Management Practices (BMPs) are stringently implemented (Lynch and Corbett, 1990). Logging methods creating less soil and vegetation disturbance can cause lower increases in erosion and resultant sediment delivery (USFS, 1981).

Ziemer and Lisle (1993) noted that although BMPs are designed to reduce pollution, such as sedimentation, they may not eliminate cumulative effects. Espinosa et al. (1997) documented that sedimentation continued to damage fish habitat even with application of a wide variety of best management practices. Espinosa et al. (1997) concluded that over-reliance on best management practices together with over-estimation of their effectiveness was a major cause of habitat degradation by land management. Thus, while management practices can reduce the level of damage caused by land-disturbance, this is only relative to "no-protection" scenario. There

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appears to be no compelling evidence that management practices can reduce the adverse effects of logging and road construction to biologically and ecologically negligible levels.

C. Forest Cutting in Riparian Areas is Particularly Detrimental

Riparian zone logging can increase erosion and sediment delivery in a number of ways:
1) increased fluvial channel erosion due to reductions in bank stability from vegetation (Graf, 1979; Hicks et al., 1991b);
2) increased frequency of mass failures (Megahan et al., 1978; Iverson and Major, 1986; Megahan and Bohn, 1989); and,
3) increased sediment transport due to the loss of sediment storage behind downed wood (Megahan, 1982, Heede, 1985; MacDonald and Ritland, 1989).

However, the majority of sediment delivered from logging activities is from roads and road construction (Megahan et al., 1978; Dunne and Leopold, 1978; Geppert et al., 1984; MacDonald and Ritland, 1989; Furniss et al., 1991) many of which are located in riparian areas.

D. Channel Erosion

Increases in peakflow will increase channel erosion via channel expansion and channel extension. Consistently increased peakflow will increase bank erosion (Packer, 1965). Montgomery (1994) documented that the contributing area above channel heads with ridgetop roads were lower than in areas without roads. This indicates that roads cause channel extension. Megahan and Bohn (1989) found that logging-induced increases in flow from logging and roads caused extension of an ephemeral channel resulting in significant erosion and sediment delivery. The erosion from channel extension accounted for most of the increase in sediment delivery caused by the logging and roads (Megahan and Bohn, 1989).

Heede (1991) documented that logging in snowmelt-dominated areas of Arizona resulted in measurable increases in the area of ephemeral channels and channel extension. Heede (1991) ascribed the expansion and extension to increased erosion in response to increased streamflow caused by logging. Dose and Roper (1994) found that low flow stream widths had increased in a statistically significant fashion with increased levels of logging with watersheds in southwestern Oregon. Dose and Roper (1994) cited increases in peakflow from logging and roads as one of the possible contributing mechanisms to the observed increases in channel width. King (1989) warned that the increased peakflow documented in granitic watersheds in Idaho could increase downstream sedimentation since sediment transport was highly correlated to peak streamflow magnitude. Although channel adjustment processes are complicated and poorly amenable to accurate prediction, it is indisputable that increases in peakflow will result in increased channel area via increased channel erosion (Schumm, 1969; Richards, 1982).

E. Water Quality

Packer (1965) concluded that undisturbed forests produce only small amounts of sediment and a streamflow suitable for drinking. Large cities such as San Francisco (Hetch Hetchy) and Portland (Bull Run) depend on water from largely or completely undisturbed watersheds. The cost of treating the drinking water from Bull Run is annually brought up when the Forest Service and/or the City of Portland proposes to conduct some forest cutting. Drinking water treatment costs can be greater than the value of timber produced. The City of Salem, Oregon, is currently studying investments in improved watershed management as being more cost-effective than large hardware investments in upgraded water treatment facilities (A. Henry, pers. comm., 1998[7]).

Forest cutting itself can produce accelerated sediment delivery, from streambank erosion related to increased peakflow, and substantial increases in stream temperatures (Packer 1965). It is likely that increased turbidity and suspended sediment is roughly proportional to the increases in peakflow (King, 1989). Considerable sedimentation also results from ill-located and/or poorly drained roads, landings, skid trails, and other disturbed areas. For example, Packer (1965) reported the results of study by researchers on the Fernow Experimental Forest Watersheds (central Appalachia) where no truck roads were built to harvest four separate treatments. Pretreatment maximum turbidity was 15 parts per million (ppm). Logger's choice skid road treatments yielded maximum turbidities of 56,000 ppm (commercial clearcut) and 5200 ppm (diameter limit cut). Extensive selection cut with forester-planned skid trails on less than 20% grade with waterbars yielded 210 ppm, a significant increase over no treatment but obviously better than logger's choice. An intensive treatment with trails designed on less than 10% grade and located away from streams yielded but 25 ppm. Packer (1965) provided evidence from several other studies to support his conclusion that the majority of sediment-related impacts due to forest operations result from roads.

In the classic Hubbard Brook (New Hampshire) study, Bormann et al. (1968) reported how a radical[8] devegetation of a small watershed did lead to large water yield increases, but at the cost of serious problems in water quality. High nutrient concentrations were found in the stream water that, in combination with increased solar radiation, caused dense algal blooms where none before existed. Important soil nutrients were lost to such an extent that they posited that the future productivity of the site would be impaired.

VII. Impacts to Forest/Soil Productivity and Reservoir Capacity

We have seen in the previous sections that soil erosion and compaction resultant from forest management operations such as thinning can have deleterious effects on baseflow, peakflow, soil properties, and water quality. Soil erosion and compaction also degrades the site productivity and can have offsite impacts such as reductions in reservoir capacity or increased costs for reservoir maintenance and water treatment.

A. Forest/Soil Productivity

Soil loss and compaction from forest management operations reduces forest productivity by loss of organic matter important for nutrient and water storage and release; direct loss of nutrients in the mineral portion of the soil; reduction of pore space available for soil and water storage, use

[7] Ashley Henry, Oregon Trout, c/o 695 Oak St., Ashland, OR 97520.
[8] Devegetation consisted of complete removal of all vegetation and the use of herbicides for three years to prevent regrowth.

and exchange with the biota; increase in soil strength impeding the growth of roots; and loss of microorganisms necessary for healthy soil and plants (Curry, 1971; Froelich, 1988; Brady, 1974).

Froelich (1988) reported a 5-15% growth reduction in 17-30 year-old stands of Ponderosa pine and a 10-50% growth reduction in seedlings from soil compaction. These reductions are for height—Froelich reported that the stand volume reductions were 69-73%. He further stated that the rule of thumb was that it takes the length of a harvest rotation to recover to normal densities. Helms (1984) reported a 59% reduction in stand volume of soils of highest bulk density over soils of lowest bulk density in his study of 15 year-old Ponderosa pine on the Tahoe National Forest. Annual shoot growth was reduce by 43% at age 2 years and 13 percent at age 15 years. A review of the literature finds that 40-70 years is required for recovery to normal density with subsoil effects taking the longest to recover.

Coats and Collins (1981), using a number of sources, estimated productive capacity losses from compaction (7.5-10%), area in roads and landings (2-15%), burning (nitrogen loss of 10% of total nitrogen storage; 0-5%), and surface erosion (cumulative 10 year loss; 15-30%) for a hypothetical management unit on steep granitic soils in California. Total productive capacity loss would be 25-60%. This loss would be persistent for at least one rotation length. Additional activities during that time would cause cumulative productivity losses.

Curry (1971) details the degradation vortex that occurs when soil loss degrades the site to the extent that its ability to reproduce vegetation of a similar type or productivity is comprised and thus longer and longer periods of regeneration are required for each succession. As an end member of this process, the researchers of the Hubbard Brook experiment report that they believed that the ability of the site to support the native vegetation had been compromised (Bormann, 1968). One of the authors recalls a silviculturalist from his days with the USDA-Forest Service remarking that he fully expected that clearcut operations (1980's style) would degrade a site one site class per rotation. Froelich (1977) confirms this in stating that skid trails are reduced to one site class below that of the surrounding area.

Thinning operations can have many of the same affects depending on the use of machinery and roads, whether the material is exported offsite, whether the thinning facilitates other degrading uses (e.g., off-road vehicles, unrestricted livestock grazing), and the near-term weather/runoff conditions.

B. Reservoir Capacity

Harrison (1991) documented the effects that soil erosion from dispersed land management activities can have on sedimentation of reservoirs. Two reservoirs on the North Fork Feather River in California accumulated 5.2 million meters3 of sediment in a 36 year period from natural and accelerated erosion. This caused operational problems and filling of about half of the capacity of the two reservoirs. Erosion of stream banks, road cuts, logged areas, and grazing lands were among the most significant contributors to the sediment problems. Approximately 70 percent of the area of the East Branch of the North Fork Feather River, identified by project sponsor Pacific Gas and Electric as the major producer of sediment, is National Forest land. Erosion control is expected to reduce future dredging cost by up to 50% and provide additional benefits such as improved water quality and fish habitat. Harrison (1991) further stated that "improved watershed management may enhance electric generation by increasing base stream flows and decreasing peak flood flows."

VIII. Resulting Impacts to Fish Habitat and Fish Survival

Forest management operations such as thinning have been shown to have negative effects on riparian areas and to increase erosion and sedimentation to streams. Packer (1965) and many since have documented the literally hundreds of studies of increased sediment delivery and increased stream temperatures to streams from forest cutting, roads, and related forest management activities. They have likewise reported the implications of such results for the quality and quantity of fish habitat and ultimately, fish survival. Regardless of the salmonid species or the metric used to characterize fine sediment concentrations, lab and field studies consistently indicate a inverse relationship between salmonid survival/abundance and fine sediment levels.

A. Increased Sediment Delivery and Sedimentation

It is known that activities that remove vegetation, compact and disrupt soils, and/or increase overland flow within watersheds, increase erosion and, hence, are likely to cause increased sediment delivery and sedimentation in downstream fish habitat (Dunne and Leopold, 1978; USFS, 1980; Swanson et al., 1987; Everest et al., 1987; Geppert et al., 1984; Everest et al., 1985; MacDonald and Ritland, 1989; Platts et al., 1989; Hicks et al., 1991b). Increases in fine sediment[9] in stream systems have multiple effects on salmon habitat that can synergistically reduce salmon survival and production. Streams that have the following characteristics are the most sensitive to increases in fine sediment: snowmelt-dominated hydrology, relatively arid climates, significant mass erosion, granitic geology, low gradient streams, steep terrain, and low frequency of large woody debris (Everest et al., 1987). Notably, many fish habitats in the Sierra Nevada exhibit just such watersheds characteristics.

Increased transport of fine sediment leads to pool in-filling (Jackson and Beschta, 1984; Alexander and Hansen, 1986; Lisle and Hilton, 1992; McIntosh, 1992) which reduces the carrying capacity of fish habitat and often reduces salmonid production (Alexander and Hansen, 1986). Streams with abundant fine sediment also typically widen over time which can exacerbate seasonal temperature extremes by increasing the stream surface area at all discharge levels (e.g., Alexander and Hansen, 1986).

High levels of fine sediment reduce macroinvertebrate productivity, reduce summer and winter rearing habitat by reducing pool volumes and interstitial rearing space, and ultimately reduce survival to emergence (STE) of fry. Most lab and field studies have indicated that the success of salmonid emergence from redds is reduced significantly as the amount of fine sediment in spawning gravel increases (Iwamoto et al., 1978; USFS, 1983; Everest et al., 1987; Chapman and

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[9] In this report, "fine sediment" refers to sediment particles <0.25 in., as defined by USFS (1983).

McLeod, 1987; Hicks et al., 1991b; Scully and Petrosky, 1991; Rich et al., 1992; Maret et al., 1993). The reduction in survival-to-emergence with increased fine sediment has been ascribed primarily to reduced flow of dissolved oxygen to the incubating eggs (Chapman and McLeod, 1987; Maret et al., 1993) or entombment of the emerging alevins within channel substrate.

Reduced STE caused by high levels of fine sediment is a significant threat because it is a source of density-independent mortality that consistently reduces salmon survival and production, even at the low seeding levels[10] existing in many streams. Reduced STE is a mortality source that is in addition to high levels of mortality from other sources. Density-independent mortality in natal habitat combined with other density-independent impacts to populations can contribute significantly to the extirpation of fish populations.

While salmon actively clean redds of fine sediment during spawning (Everest et al., 1987; Chapman and McLeod, 1987), subsequent sedimentation in the redds by fine sediments is highly likely during the incubation period, especially when ambient surface fine sediment levels are high. Removal of intruded fine sediment at depth appears to require flows that would entrain all the sediment particles in the channel substrate at depth in the bed (Diplas, 1991); this would probably scour redds. Overwinter sedimentation of salmonid redds have been documented by a number of studies in snowmelt-dominated watersheds with relatively high levels of fine sediment (Reckendorf and Van Lieuw, 1989; King et al., 1992; Maret et al., 1993; Rhodes and Purser, in process). Notably, in snowmelt-dominated streams, winter streamflows are relatively low.

B. Cumulative Effects of Forest Cutting on Fish Habitat and Survival

In addition to increasing sediment delivery and potentially reducing baseflow (e.g., Hetherington, 1982) forest cutting can also lead to increased stream temperatures (Hicks, et al., 1991a; Fowler, et al., 1987), low dissolved oxygen and simplified habitat creating direct negative effect on fish, including mortality. In addition, reduced streamflow exacerbates the effects of increased stream temperatures and low dissolved oxygen and reduces the quantity of habitat available for use. Finally, as streams dry, fish are forced in smaller areas such as remnant pools and may suffer from increased competition and predation (Hicks, et al., 1991a).

IX. Alternative Actions to Increase or Protect Baseflow

Forest thinning is unlikely to provide measurable, predictable, and consistent increases in baseflow, and it will likely have other unavoidable and negative impacts. Therefore, we propose alternative actions which are known to increase infiltration, slow stream velocities, increase groundwater storage of peakflow to become available as baseflow, improve water quality, contribute to reductions in peakflow and the consequent potential for destructive downstream

[10] Habitat seeding level refers to the percentage of available habitat which is used for spawning. Reductions in seeding of habitat has been one argument for not improving habitat conditions since, apparently, there is more than enough habitat to go around. However, this specious argument does not allow for recovery which will require habitat amounts orders of magnitude greater than that which exists today nor does it recognize that the poor habitat conditions create poor water quality conditions downstream and may in fact be causing low seeding levels.

flooding, and improve salmonid habitat in support of recovery of listed, proposed, or otherwise desirable species. Many of these alternatives work together and have synergistic effects.

A. Cessation of Roadbuilding and Increase Road Obliteration

As an example of the effects of roads, paved and gravel roads in the forest environment of the Sierra Nevada are assumed to occupy 5% of the approximately 30,000 square miles constituting the forested area from Mt. Lassen to Mt. Whitney. This means that an average of 50 inches of precipitation is falling on about 1500 square miles of essentially impervious land. Since the majority of roads are located adjacent to streams, much of this precipitation or snowmelt is routed quickly to streams bypassing the groundwater/baseflow system altogether. If half of this precipitation or snowmelt is routed more or less directly to the stream, this adds up to 2 million acre-feet to the peakflow and/or storm runoff system over pre-road conditions.

The increase in peakflow obviously contributes to flooding which has caused severe problems to people living on the floodplain in recent years and entrains thousands of tons of surface and bank eroded sediment to end up in stream channels, farmers' fields, parking lots, and reservoirs. The increased bank erosion puts private and public property and facilities at risk and simplifies fish habitat putting Threatened and Endangered species at risk as well.

Reducing this road mileage by 10 percent and rehabilitating the former road surfaces to infiltrate water could result in as much as 200,000 acre-feet—or one foot of water over 500 square miles—of additional baseflow.

B. Protect High-quality Soils and Restore Compacted and Eroded Soils

The reasons and methods for protecting soil from erosion and compaction are well known. The existing condition is one in which thousands of acres of forestland in the Sierra are already compacted from past logging operations. Meadows and steep slopes have been particularly hard hit by the combined impacts of logging and unrestricted livestock grazing. The effects are seen in regeneration problems, type conversion due to greatly decreased soil moisture storage, fertility problems, incised channels, degraded fish habitat, and downstream flooding and sedimentation.

Machinery should be restricted from any area not already compacted. Riparian areas should have large buffers (at least 300 feet on each side of the floodplain/channel [where there is no floodplain]) and should include headwater areas 300 feet on each side of zero-order axis. Restrictions in riparian areas should also include suspension of livestock grazing (see below), reducing the number of organized campsites, and reducing roads while prohibiting additional road construction.

These recommended restrictions may seem radical, but are no more so than continuing to shift the externalities of conventional forest management to downstream users—people and fish, and federal and state taxpayers (e.g., Endangered Species Act and Clean Water Act bureaucracies, flood control structures, flood cleanup). Most pertinent to the current topic, they are the actions that should be taken if there is a genuine desire to increase baseflow while protecting or improving water quality and fish habitat.

C. Restore Beaver Populations

Many if not most meadows in the subalpine zone of the Sierra are suffering the effects of beaver removal and unrestricted livestock grazing for the last 150 years. Mountain meadows in the Sierra Nevada have been used intensively for livestock since at least the 1880's and show the effects today. Few, if any, intact vegetative communities remain, all having given way to annual "weeds" (e.g., Senecio spps.), bare soil, introduced grasses (e.g., Poa spps.), and deeply incised streams with largely denuded banks. The majority of herbaceous has been allocated by the National Forests to livestock and compaction is rampant over the landscape. Riparian areas and fish habitat have been significantly damaged or utterly destroyed by grazing (Knapp and Mathews, 1996).

The missing beaver populations formerly dammed meadow streams creating wet meadows with ponds and a full groundwater storage component. Beaver dams create hydraulic head which forces surface water into the meadow's groundwater through root channels, soil pipes, and large soil pores. Groundwater follows the gradient down around the dams and exits as streamflow later in the year (Lowry and Beschta, 1994). This was previously an important mechanism for turning snowmelt-driven peakflow to baseflow for summer streamflow. The beaver maintain their own facilities, use and grow native vegetation which could be readily available, provide flood control and increased baseflow (of cooler temperature), and as a bonus, beaver ponds have been observed to provide excellent salmonid rearing habitat.

A meadow restoration project with which the authors are familiar yielded cooler stream temperatures, higher groundwater surfaces in meadow adjacent to beaver habitat, greater channel storage of winter precipitation and snowmelt runoff, and improved moisture conditions for native meadow vegetation in the first year of implementation. As regards sustainability, the beaver habitat portion of the project is largely self-perpetuating.

D. Suspend or Greatly Reduce Livestock Grazing

In their review of potential strategies for baseflow augmentation, Ponce and Lindquist (1990) concluded that excluding livestock from degraded areas was documented to increase baseflow and that improved range management is one of the most promising strategies for increasing baseflows. Grazing contributes to reduced baseflows by compacting soils, significantly elevating soil loss (Lusby, 1970), and incising streams which reduces water table elevations (Ponce and Lindquist, 1990; Platts, 1991). Recent data (Boone Kauffman[11], pers. comm., 1998) supports past research (e.g., Springer and Gifford, 1980) by showing increases in bulk density of grazed areas ranged from 15 to 50% compared to ungrazed areas. Infiltration rates were 3 to 12 times higher in ungrazed areas than in grazed areas of the Middle Fork of the John Day River watershed. Long term suspension of livestock grazing, particularly in riparian zones, would have

[11] Dr. Boone Kauffman, Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97331.

the effect of reducing surface runoff and, by routing precipitation and overland flow from upslope through the soil to the groundwater, increasing baseflow.

Notably, recovery of degraded conditions in riparian areas is unlikely without several years of rest followed by a compatible grazing strategy with reduced livestock numbers that is intensively monitored (Platts, 1991). Even then it is likely that continued grazing will retard the recovery of vegetation and soils that is necessary to allow hydrologic recovery and attendant benefits. In highly degraded areas or where endangered species are affected, grazing should be suspended until recovery has occurred (Clary and Webster, 1989; Anderson et al., 1993; Henjum et al., 1994; Rhodes et al., 1994). Reduced grazing pressure also has several other benefits, besides contributing to increased baseflow: improved water quality and stream conditions for fish, reduced peakflows, and higher soil productivity (Platts, 1991).

X. Conclusion

In summary, if thinning were conducted on a scale significant enough to increase annual yield, it would be accompanied by increases in flooding, erosion, permanent loss of soil storage, loss of forest productivity, reduced water quality, and increased frequency of local extinction of sensitive aquatic species. This would be unacceptable from an economic, environmental, social, and even legal viewpoint. And still, a desired effect of increased summer streamflow (baseflow) would likely not be realized except possibly as a transient effect, while the negative effects are likely to persist for far longer.

There is much to be learned about the effects of forest management in the Sierra Nevada. If thinning effects are to be scrutinized, studies should involve small-scale thinning in areas that do not affect fish populations and should be monitored fully over long time periods prior to any larger scale application. As Hicks et al. (1991) noted, there have been very few long-term studies of the hydrologic effects of logging. It appears that several decades are needed to fully elucidate effects (Hicks et al., 1991a). However, the watershed and embedded resources in the Sierra have already been significantly and adversely modified. Therefore, the most prudent course of research is to do experiments that do not risk potential additional adverse and irreversible modifications. Particularly useful would be to fully implement actions known to improve watersheds (road obliteration, no new roads, no logging, suspension of grazing at the watershed scale, etc.) and monitor effects for several decades.

In closing, the irreversibility of actions proposed to be taken and the negative impacts (compaction, productivity loss, sedimentation, biological impacts) which could last 40-10,000 years are certain, while the benefits are speculative, and may be transient at best.

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